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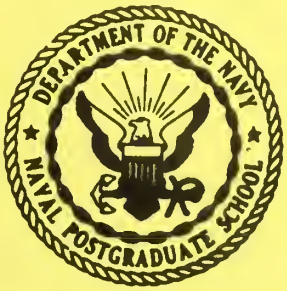

THE THIRD EUROPEAN CONFERENCE

ON CONTROLLED FUSION AND PLASMA PHYSICS

by

F. Schwirzke

21 August 1969

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ABSTRACT:

In Part A of the report the titles of the 12 sessions and the 5 invited lectures are summarized in the introduction. Concerning the content of the 117 presented papers, mainly the ones dealing with collisionless plasma phenomena are reviewed in the report, as for example: collisionless plasma heating by strong shock waves, turbulent heating, fluctuation spectrum during turbulent heating of a toroidal plasma, transformation and absorption of high frequency waves in a plasma, observation of anomalous resistivity, etc. Furthermore, an interesting effect concerning the anomalous scattering of laser light from a plasma is reported. The last chapter reviews a panel discussion on Tokamaks which started with a report on recent results given by L. A. Artsimovich and B. B. Kadomtsev.

Part B contains the paper No.111, "Investigation of Instabilities and Collisionless Damping Mechanisms in the Front of a Laser Produced Plasma Interacting with a Magnetic Field" by F. Schwirzke, published in Proceedings Third European Conference on Controlled Fusion and Plasma Physics, Wolters-Noordhoff Publishing, Groningen, The Netherlands, 1969.

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PART B

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Report on the 3rd European Conference on Controlled Fusion and Plasma Physics and the Symposium on Beam Plasma Interactions in Utrecht, The Netherlands, 23-27 June 1969

by F. Schwirzke

I. Introduction

The conference was a third in a series in which the previous two took place in Munich in 1965 and in Stockholm in 1967. The first Symposium on Beam-Plasma Interaction was held in Prague in 1967. One hundred and seventeen papers were selected for presentation by a Paper Selecting and Program Committee. The papers were arranged in groups of related subjects. Each morning session began with an invited lecture. The selected papers were presented in two parallel sessions. The titles of the sessions were

(1) Stellerators and Multipoles,
(2) Open Ended Systems,
(3) Beam Plasma Interactions,
(4) Theory,
(5) Rotating Plasmas and Arcs,
(6) HF-Plasma Interactions,
(7) Pinches and Tokamaks,
(8) Waves,
(9) Nonlinear Phenomena,
(10) Laser Produced Plasmas,
(11) High Density Plasmas and Accelerators,
(12) Driftwaves.

The five invited lectures were entitled:

(1) A Survey of Stellarator Problems by G. V. Gierke - Germany.
(2) Beam-Plasma Interaction Studies by A. Bers - M.I.T., USA.
(3) Absorption of High-Frequency Waves in Plasma by V. E. Golant - U.S.S.R.
(4) Review of Culham Theta-Pinch Experiments by H. A. E. Bodin - England.
(5) Nonlinear Behavior of Plasma Under the Influence of Large-Amplitude Waves by I. Fidone - France.

The following countries contributed papers: England - 24, USA - 16, U.S.S.R. - 16, West Germany - 16, France - 13, The Netherlands -99, Italy - 5, Czechslovakia - 4, Sweden - 3, Poland - 2, Japan - 2, and one paper each from Austria, Belgium, Denmark, East Germany, Norway, Switzerland, Yugoslavia. The meeting was organized by the FOB - Institute for Plasma Physics at Jutphaas, The Netherlands. The conference was held in English and no translation facilities were available. It is amazing that France and the U.S.S.R. agreed with this arrangement. Obviously there exist some anologies between the European meeting and the annual meetings of the Plasma Physics Division of the American Physical Society. In fact the European Physical Society held a meeting to consider the possibility to form a plasma physics division of the European Physical Society. There is a possibility that the European Physical Society will at some time take over the responsibility for the European Conferences which are now formed by self appointed groups and committees. A European Committee on plasma Physics has been formed consisting of the following members:

C. M. Braams	The Netherlands
B. Brunnelli	Italy
B. Lehnert	Sweden
R. S. Pease	United Kingdom
R. Z. Sagdeev	U.S.S.R.
A. Schlüter	W. Germany
J. Teichmann	C.S.S.R.
P. Thonemann	United Kingdom
M. G. Trocheris	France
P. Vandenplas	Belgium
E. S. Weibel	Switzerland

II. Collisionless Plasma Phenomena

Concerning the content of the presented papers, it is interesting to note that about 10% of the papers gave experimental results on collisionless phenomena in a plasma like collisionless plasma heating by strong shock waves,

turbulent heating, transformation and absorption of high frequency waves in the plasma, observation of anomalous resistivity, etc.

a. Golant, U.S.S.R. reported on the transformation and absorption of high frequency waves in a plasma. The applications of high frequency waves for heating plasma to high temperatures are based on the collisionless absorption mechanism as cyclotron and Landau damping. Strong cyclotron damping at frequencies near to the electron and ion cyclotron frequencies has been used in many experiments on high frequency heating. Direct collisionless absorption of an incident wave outside the range of cyclotron resonance is weak when the plasma temperature is low. That means when the thermal velocities are much less than the light velocity. Strong absorption in these conditions can be obtained only as a result of transformation of the incident wave into a plasma wave propagating at small phase velocity, which is then strongly absorbed by the plasma. Theoretical considerations show that a linear wave transformation is possible in an inhomogeneous one-dimensional plasma in the region where the refractive index for the wave propagation in the direction of the density gradient goes to infinity. At a given plasma density there exist three frequencies at which the refractive index turns to infinity. Accordingly, in an inhomogeoeous plasma with density varying from 0 to the maximum value, there must exist three bands of transformation. Collisionless absorption of electromagnetic waves by a plasma in the frequency range between electron-cyclotron and upper hybrid frequency as well as at a frequency somewhat lower than the electron-cyclotron frequency was observed experimentally. Experiments on wave absorption in a plasma were also conducted near the lower hybrid frequency. The results obtained are in agreement with the assumption that the absorption is connected with a linear wave transformation. The principle results which gave evidence of this agreement are:

(1) The absorption ranges are consistent with the theoretical boundaries of the wave transformation ranges.

(2) The absorption has a threshold character. The absorption increases when the density and the magnetic field approaches the values which are within an absorption range. The magnitude of the absorption efficiency is in agreement with the calculations of the transformation efficiency for a plasma with transverse dimensions smaller than the wave lengths.

(3) The location of the effective absorption ranges is not connected with the conditions of wave excitation, but depends on the angle between the density gradient and the magnetic field.

(4) The wave absorption efficiency depends only slightly on the collision frequency and on the particle temperature when these parameters are varied within a wide range of values. The absorption of the high frequency electromagnetic wave depends only weakly on the intensity of the wave. Since the transformation efficiency does not depend on the temperature,wave transformations may be used for heating a plasma up to high temperatures in the thermonuclear range.

b. Turbulent heating experiments with a plasma produced by a hollow-cathode arc were reported by H. De Kluiver, FOM-Institute for Plasma Physics, The Netherlands. The arc runs along the axis of a magnetic mirror. The turbulent heating of the plasma is brought about by the application of an axial electric field generated by the discharge of a capacitor bank of 1.9 μF, 40 kV, and a rise time of .7 microseconds. Turbulent heating is observed when the capacitor voltage exceeds a critical value which depends on the plasma density. Turbulent heating has been observed in argon, helium, and hydrogen. The turbulent state is characterized by an increased resistivity and strong electromagnetic radiation from the plasma. The perpendicular energy gain of the plasma is derived from diamagnetic loop signals. The increase corresponds

to about 7% of the capacitor energy. Only during the turbulent state a significant part of the x-ray emission has an energy above 50 keV as is concluded from foil absorption measurements. It is assumed that the heating process is limited by the tube diameter and by the magnetic field available which was a mirror field of 8,000 gauss with a mirror ratio 4. When the perpendicular energy of the electrons and ions increases the particles will hit the wall within a few microseconds. The plasma dissipation at the wall is accompanied by a rapid decrease of the plasma pressure and enhanced x-ray emission at higher energies.

Plasma turbulent heating in a toroidal machine by a current has been reported by the Zinoviev from the Kurchatov Institute in Moscow. The initial plasma was produced by a quasi-stationary current of 1 to 3 kAmps in a magnetic field of B = 4-6 kilogauss. The diameter of the plasma column was defined by a 4 cm diaphragm. The hydrogen pressure was 4×10^{-4} to 1.5×10^{-3} torr. The electron density was within the range of $2 \times 10^{13} - 10^{14}$ cm^{-3}. The electron temperature was of the order of 5 eV. A short pulse of voltage was induced in the plasma by a discharge of a condenser of 19 μF. The duration of the pulse was about .3 μsec. If the electromagnetic field is applied along the direction of the quasi-stationary current, the total current strongly increases up to a value which is four times larger than the initial level. The electric field rises from .5 volts per centimeter up to 40 volts per centimeter and decreases then to a value close to zero. This drop must correspond to a sharp increase in the plasma conductivity. The temperature is estimated from diamagnetic signals, $T_e + T_i \approx 300 - 500$ eV. It has been observed that the increase of the anomalous resistance occurs within .1 μsec and is accompanied by an intense increase of the plasma energy. A relation between heating and the excitation of ion acoustic instability has been established. This

turbulent heating method is of interest for a toroidal current system of the Tokamak type.

c. The fluctuation spectrum during turbulent heating of a toroidal plasma has been investigated by J. Jancarik, et al, Culham Laboratory, England. Again the plasma density was in the range between 10^{12} to 10^{13} cm^{-3}. The heating current pulse, which lasts about 300 nsec, is produced by electromagnetically inducing a large axial electric field of about 300 V/cm in the plasma parallel to a magnetic field of 3 kilogauss. The plasma column exhibits anomalously high resistivity which depends on the plasma density and ion mass. The observations have been made both in hydrogen plasma of density $10^{12} cm^{-3}$ for which the discharge is highly resistive and which reaches a maximum temperature of about 10 keV and in argon at a higher density of 5×10^{12} cm^{-3} for which the plasma resistivity is smaller and the maximum electron temperature lower, in the order of several hundred eV. Strong microwave emission has been observed at the time at which the turbulence is strongest. The potential fluctuations parallel to the current flow were measured with a double electric probe consisting of two platinum electrodes of .1 mm diameter, 0.5 mm long, and .35 mm separation. Since the frequencies and growths rates are higher for hydrogen, direct measurements are difficult and so far have been performed mainly in argon. Distinct maxima in the spectrum have been observed at about 50 MHz and 75 MHz. The first is ascribed to an ion acoustic wave with a phase velocity $C_s = \omega_s/k_s = \sqrt{kT_e/M} \approx 3 \times 10^6$ cm/sec, or $T_e \simeq$ 300 eV. The higher frequency corresponds to the ion frequency ω_{pi} for the measured density 5×10^{12} cm^{-3}. During the early part of the discharge, frequencies larger than ω_{pi} have been observed, which seem to arise from a two stream instability. Density fluctuations have been studied by microwave scattering.

d. Observation of collisionless plasma heating by strong shock waves in a Theta-pinch discharge has been reported by M. Keilhacker, Garching, Germany. The heating of the plasma by collisionless shock waves was investigated by measuring the variation of magnetic field with magnetic probes and determining the density and electron temperature from Thompson scattering of laser light. The compression waves are produced in a tube of 14 cm diameter by a fast rising magnetic field (12 kilogauss in .5 microseconds). The shock fronts are almost stationary and propagate with Mach numbers of 2 to 3 through a highly ionized hydrogen or deuterium plasma. Direct measurements of density and electron temperature in the shock wave using the Thompson scattering of laser light show that only 20% of the measured electron temperature can be ascribed to at the adiabatic heating and resistive heating based on binary collisions, e.i., the results indicate a high turbulence plasma resistance. From a comparison of the measured shock width with the mean free path for Coulomb-collisions, it was concluded that the shock waves were collisionless. The effective collision frequency in the turbulence state is about 2 orders of magnitude higher than the frequency for electron-ion collisions and approximately equal to the ion plasma frequency. This indicates that in the observed shock waves the main dissipation process is resistivity which provides the transfer of directed kinetic plasma energy into thermal energy of the electrons. The exact mechanism that causes the anomalous plasma resistance is not yet known. The most probable process is the excitation of plasma waves by electron-ion streaming or the occurrence of ion acoustic instabilities in the shock front where the current density is large.

III. Anomalous Scattering of Laser Light from a Plasma

An interesting effect concerning the anomalous scattering of laser light by a steady state plasma was reported by H. Ringler, Garching, Germany. The theory of scattering electromagnetic waves by a plasma satisfactorily accounts for the observed back scatter profile of a radar pulse from the ionosphere. Several laser light scattering experiments were performed in laboratories and the observed scattered spectra were consistent, within the experimental errors, with the theory. Now, Ringler reports measurements which show large and significant departures from the theory. The plasma is formed in a magnetically stabilized electric arc. A magnetic field of 10.8 kilogauss is imposed parallel to the axis of a high current arc discharge. The arc is operated at an initial pressure of 10 torr of hydrogen. Temperatures of 10 eV and electron densities of up to 10^{16} cm^{-3} have been measured. Light from the Q-spoiled ruby laser is focused at a small volume element in the plasma. The scattered light is observed perpendicular to the incident beam and the arc axis. The most remarkable feature in the scattered spectrum is the presence of satellite lines while the plasma parameters are such that no satellites should appear. The position and the relative magnitude of the satellites are apparently independent of the laser power. As a consequence of the observation that the scattered intensity is not a linear function of the incident power, and the occurrence of the satellites the author concludes that the electron density of the plasma cannot be reliably predicted by the scattering theory. The author assumes that the peaks occur at the harmonics of the plasma frequency. To check that the satellite position is dependent on the local electron density the experiment was repeated at a volume element 8 mm off the center of the discharge where the electron density and temperature are lower. Again

several peaks were observed but this time the wave length shift was smaller corresponding to the lower electron density. During my visit of the Plasma Institute in Garching, W. H.V. Kegel suggested in a private discussion another explanation of the observed anomalous scattering spectra. He calculated scattering spectra under the assumption that beside the main group of plasma electrons of a given temperature a small fraction of about 5% exist of different, lower temperature. Correspondingly the Debye length, λ_D, is smaller and the scattering parameter α becomes larger. α is defined by $\alpha = \frac{\lambda}{4\pi \lambda_D \sin \theta/2}$ where λ is the wave length of the incident light and θ the scattering angle. The satellites may result from the cold plasma electrons when the value of α for this component becomes larger than 1.

IV. Tokamak

Certainly one of the highlights of the conference was an unscheduled, informal panel discussion on Tokamaks with a report on recent results given by Artsimovich and Kadomtsev. Artsimovich described the Tokamaks and presented the experimental results obtained from the two machines T-3 and TM-3. The Tokamaks can produce plasmas where both the density and temperature are high. In the largest machine, T-3, a current pulse of 100 kAmps and lasting for 65 milliseconds flows in the plasma. This current produces in the toroidal machine a magnetic field in ϕ- direction. A toroidal field in θ- direction of 35 kilogauss is produced by external currents. In addition another external field which is perpendicular to the plane of the torus can be applied to position the plasma column along the axis of the torus. The current in the plasma has three functions, (1) production of the plasma, (2) heating of the plasma, (3) confinement of the plasma. The Tokamak machines

become reproducible and give good confinement if the necessary and sufficient condition for MHD-stability, the Kruskal-Shafranov condition is fulfilled,

$$q = \frac{B_\theta}{B_\phi} \frac{r}{R} > 1 \qquad (1)$$

where R is the major radius of the torus and r the distance from the magnetic axis. This condition has to be fulfilled for every point within the plasma. If r_o is the radius of the plasma column than

$$\frac{B_\theta}{B_\phi} \frac{r_o}{R} > q \qquad (2)$$

Some margin of the stability is given for $r = r_o$, if $q > 2\text{-}3$. The fulfillment of the Kruskal-Shafranov condition implies that the machine has an average minimum -B configuration. As a new result Artsimovich reported that the duration of the current pulse has been extended from 35 msec to about 65 msec. As a consequence the ion temperature increased from 300 eV as was reported a year ago at the Conference on Plasma Physics and Controlled Nuclear Fusion Research at Novosibirsk, (1968), to about 400 to 450 eV. The electron temperature is about 1 keV. This increase of the ion temperature with the increased length of the current pulse is highly promising because it indicates that even higher temperatures in the thermonuclear range may be obtained by increasing the duration of the current pulse. The electrons in the Tokamak machines are heated resistived by the current while the ions are heated by classical Coulomb-collisions with the electrons as evidenced by a comparison of the heating rates in deuterium and hydrogen at higher pressures. The ion temperature increases slowly with density. However the experiments show that there is a limitation in the range of density for which a stable confinement exists which is between 3×10^{12} and 4×10^{13} cm^{-3}. The best results were obtained at 3×10^{13}. At this density the measured ion temperature can be explained by the balance between the possible energy transfer rate from the

hot electrons due to classical Coulomb collisions and the loss rate of ion energy due to classical heat conduction and diffusion. In conclusion the plasma behaves classical in this density range. At a density $n \approx 3 \times 10^{12}$ cm^{-3} a total disagreement exists with classical theory and the energy loss rate is probably enhanced by an instability. In this density range an anomalous resistivity has been observed which is larger than the classical resistivity by a factor of 30 to 50. However, also at the density of stable confinement, $n \sim 3 \times 10^{13}$ cm^{-3}, the resistivity is still 3 to 5 times larger than the Spitzer value for the measured temperature. Obviously, there is still some turbulence present in the plasma but the level is not large enough to destroy the confinement in the average minimum-B configuration. In fact under those circumstances the anomalous resistivity is welcome because it increases the efficiency of the heating process of the electrons. It is possible that the anomalous resistivity could partly be explained by the effect of impurities in the plasma. Above a critical density of about 4×10^{13} cm^{-3} an anomalous shift of the equilibrium position of the plasma column toward the outer wall has been observed. It is not possible to get a stable plasma ring at densities which are larger than this critical value. This lack of equilibrium is not well understood. There are some indications that the value of the critical density depends on the initial condition of the discharge. Maybe the initial condition freezes into the plasma with increasing conductivity during the heating process. However, that assumption doesn't explain what kind of inhomogeneity really causes the drift of the plasma ring to the wall.

If possible two different diagnostic methods should be used in plasma physics to be confident that the measured values are sound results. In the

Tokamak experiments the electron temperature was deduced from diamagnetic probes and plasma conductivity measurements. The diamagnetic probes gave an electron temperature of 1 keV which was larger than the electron temperature determined from the effective conductivity which was only 200 to 300 eV. In this case the diamagnetic determination of T_e is reliable while the low value of T_e from the conductivity measurement shows the influence of the anomalous resistivity. The ion temperature was deduced by analyzing the fast particles which escaped from the plasma by charge exchange. As a second method the ion temperature was determined from the thermonuclear neutron emission from the plasma which is a rather sensitive function of the ion temperature. The neutron emission shows no fluctuations or irregularities beside statistical deviations which indicates a stably confined plasma. The two ion temperatures determined from charge exchange and neutron measurements agree for the 30-40 msec during which neutron emission occurs. On the other side the ion distribution function shows the existance of two different ion temperatures. The lower one is about $T_i \sim 100$ eV and the higher one in the order of 300 to 400 eV. This existance of two groups of ions of different temperatures is rather disturbing and no reasonable explanation has been offered. Certainly, the neutrons are emitted by the high energy tail in the distribution function. Artsimovich indicated that an ion temperature gradient exists between the axis and the outer radius of the plasma column.

The plasma density was determined by microwave interferometers operating at the wavelength of 2 millimeter. Twenty different rays allowed the determination of the plasma density as function of the radius.

Recent results on the energy confinement time at higher currents and fields were presented. The energy confinement time, τ_E, is defined by

$$\frac{dW}{dt} = Q_{Joule} - Q_{Loss} \qquad (3)$$

where $Q_{Loss} = \frac{W}{\tau_E}$. W is the energy of the plasma. Q_{Joule} represents the resistive heating rate of the plasma by the axial current. The energy loss from the plasma is due to radiation, charge exchange, diffusion, and thermal conductivity such that

$$\frac{1}{\tau_E} = \left[\frac{1}{\tau_{rad}} + \frac{1}{\tau_{ch.ex}} \right] + \frac{1}{\tau_D} \qquad (4)$$

The loss rates due to radiation and charge exchange are independent of the confining magnetic field configuration. The diffusion processes described by τ_D indicate if there exists stable confinement of the plasma or not. The total energy losses from the plasma to the diaphragm and the walls of the vacuum chamber were measured separately. The measurement showed that about 1/2 of the energy of the plasma is lost by radiation and charge exchange while the other half is lost by diffusion and heat conduction. Since

$$\tau_E \approx 15 \text{ msec it follows } \tau_D \approx 30 \text{ msec.}$$

For an electron temperature of about 1 keV this confinement time τ_D is about 100 times larger than τ_{Bohm}. If the heating of the ions is due to classical Coulomb-collisions between the hot electrons and the ions of lower temperature then the ion temperature is determined by

$$\frac{dW_i}{dt} = A \frac{n}{T_e^{3/2}} (T_e - T_i) - Q_{Loss} \qquad (5)$$

where A = constant and $W_i = 3kT_i/2$. Assuming a quasi-stationary ion temperature and all plasma losses caused by the ions, Q_{Loss} becomes approximately

$$Q_{Loss} \sim \frac{An}{T_e^{3/2}} (T_e - T_i)$$

The ion thermal conductivity losses have been calculated by Sagdeev and Galeev for a cyclindrical and a toroidal plasma configuration. Taking the parameters of the stable plasma $n = 3 \times 10^{13}$ cm^{-3} and $T_i \sim 300$-400 eV, computer calculations show that the observed losses agree within a factor of 2 with the Sagdeev-Galeev theory. In conclusion, classical processes determine the energy loss rates from the plasma. The observed empirical scaling laws for τ_E are of great importance for achieving the goal of longer confinement times and higher temperatures which would make finally a fusion reactor possible. The experiments show that τ_E increases with the duration and the intensity of the current pulse.

Kadomtsev discussed the MHD-equilibrium in the toroidal system and the possible loss mechanisms at high and low plasma densities. He stressed that the energy loss in the stable density range is well described by the classical theory of the ion thermal conductivity. It is possible that the plasma losses at low density, $n < 3 \times 10^{12}$ cm^{-3} are caused by runaway electrons. The observed anomalous resistivity of the plasma may be caused at high magnetic fields by an ion sound instability if two groups of ions of different temperatures are present in the plasma. In conclusion, the Tokamak machines confine a hot relatively dense plasma for about 100 Bohm times. However, there still exist a number of unsolved problems, concerning for example the equilibrium of the plasma column, the anomalous resistivity and the resulting turbulent heating, the existence of two ion temperatures, the actual shape of the ion temperature gradient,and the mechanism which destroys the confinement above the critical plasma density. The comparison with the Bohm diffusion time depends sensitively on the value of T_e which was measured by diamagnetic probes only. At present an experimental group from Culham tries to determine the electron and ion temperature and the plasma density by Thompson scattering of laser light from the plasma.

INVESTIGATION OF INSTABILITIES AND COLLISIONLESS DAMPING MECHANISMS IN THE FRONT OF A LASER PRODUCED PLASMA INTERACTING WITH A MAGNETIC FIELD

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The two problems of creating and confining a high temperature plasma in a magnetic field configuration are usually closely linked together and a laser produced plasma is no exception. Theoretical calculations[1-3] and experimental results[4-8] show that energy from a giant laser pulse can be absorbed by a small target within a few nanoseconds thus creating a high temperature plasma. Obviously the next step is then to investigate the interaction of the expanding plasma with a magnetic field. This interaction is of special importance in the CTR program where the purpose is to confine a thermalized hot plasma in a stable magnetic field configuration. A laser produced plasma which expands across a magnetic field also uncovers new extensive possibilities for the investigation of instabilities and collisionless damping mechanisms in the wave front. If a low density (collisionless) background plasma is present, then the "exploding" laser plasma acts as a very fast piston and collisionless shockwaves can be studied.

In the initial expansion phase of the $\beta \gg 1$ plasma the temperature decreases rapidly $T_r = T_o(r_o/r)^2$, where T_o and r_o are the temperature and radius of the plasma when it ceases to absorb laser energy. Most of the energy content of the plasma shows up as kinetic expansion energy. Mainly surface currents in the wavefront provide the possibility to thermalize the expansion energy again by resistive effects. If the electron Coulomb-collision frequency ν_e becomes smaller than the growth rate, instabilities may develop in the front and contribute effectively to the energy dissipating process. ν_e remains constant in the expanding plasma if resistive heating can be neglected. According to Spitzer[9] $\nu_e = n_r Z^4 \ell n\, \Lambda / 0.266\, T_r^{3/2}$, where T is in ^oK. Z is the ionic charge. For a spherically expanding plasma with a homogenous distribution of N electrons $n_r = 3N/4\pi r^3$. Introducing n_r and T_r and assuming $Z = 1$ and $\ell n\, \Lambda \approx 10$ we obtain a r-independent expression for $\nu_e \approx 9N/(T_o r_o)^{3/2}$. However, taking into account the resistivity, T_r increases again after the initial sharp drop which is due to the adiabatic expansion over the first few mm, and hence, ν_e decreases with further expansion. The two-stream instability has a large growth rate $\gamma \approx \omega_{pe}(m/M_i)^{1/3}$

and has a chance to develop if $\nu_e < \gamma$. ω_{pe} is the plasma frequency, m and M_i are the electron and ion mass. Furthermore, the criterion for instability requires that the current associated ordered velocity of the electrons in the wavefront becomes larger than their mean thermal velocity. The growth time of the two-stream instability $\frac{1}{\gamma}$ is rather small in comparison with the propagation time of the wavefront which is in the order of $\tau \approx 10\ (c/\omega_{pe}V_A)$, where V_A is the Alfven velocity and $d \approx 10\ c/\omega_{pe}$ is of the order of the characteristic width of the front when the resistivity of the plasma is determined by the turbulence caused by the instability. If $\gamma\tau >> 1$ a steady state will exist within the wave front and the onset of the instability can be studied locally. Considering a stationary wavefront which is common to shock theory, propagating in r-direction across the magnetic field, the electric current is perpendicular to B and r in the θ direction and is given by Maxwell's equation $j = -enV_{e\theta} = -(c/4\pi)dB/dr$. Substituting $\omega_{pe}^2 = 4ne^2/m$ and $K = \left|(1/B)dB/dr\right|$ where $K = \pi/d$, the instability criterion $V_{e\theta}^2 > T_e/m$ becomes $d < (\pi c/\omega_{pe})\ (2/\beta)^{\frac{1}{2}}$ where $\beta = (8\pi nT_e/B^2)$. This condition will be satisfied at a certain radius since n decreases rapidly during the expansion of the laser produced plasma. If we want to compare the instability criterion with the measured width, d, of the front of the expanding plasma we have to introduce the ω_{pe} and β values which exist within the wavefront where $V_{e\theta}$ has a maximum, i.e. where the pressure gradient has a maximum, $d^2p/dr^2 = 0$. We can assume that at the turning point $\omega_{pe}^2 \approx (1/2)\omega_{per}^2$ and $\beta \approx (1/2)\beta_r$ where ω_{per}, β_r are the quantities at the edge of the plasma which can be determined rather easily in the experiment at a given radius. Thus,

$$d < 2\pi(2/\beta_r)^{\frac{1}{2}}(c/\omega_{per}). \qquad (1)$$

The plasma was produced by a 150 MW, 20 nsec Nd-laser pulse which was focused on the tip of a pyrex fiber of 30 μdiam. About 1 joule was absorbed by $N = 10^{16}$ target atoms. The velocity of the expanding plasma (10^7-10^8 cm/sec) depends on the absorbed laser energy. The observed velocities are comparable with the ones obtained in θ-pinches which have been used so far exclusively to study collisionless mechanisms in laboratory plasmas. A 1 mm diam moveable magnetic probe was used to measure the expansion velocity and the width of the wavefront. Fig. 1 shows an oscilloscope trace of the magnetic signal. An increase of B is observed before the diamagnetic signal is recorded in positive, upwards direction, i.e., the expanding plasma compresses B like a piston and thus produces an increase of the magnetic field. A steep front exists as indicated in the sudden increase of the

diamagnetic signal. Assuming a homogeneous distribution of $N = 10^{16}$ electrons and an ionization level of $Z = 1$ over a sphere of $r = 1.5$ cm, the density would be $n_r = 7 \times 10^{14}$ cm^{-3}. In reality a density profile exists and a reasonable estimate gives $n_r \sim 3 \times 10^{14}$ cm^{-3} and $\omega_{per} \approx 10^{12}$. Introducing these values into criterion (1) we find that the two-stream instability should occur if $d < 0.46$ cm. From the measured expansion velocity $V = 10^7$ cm/sec and the rise time of the diamagnetic signal in Fig. 1 we observe a width of $d = 0.4$ cm $= 13.3\ c/\omega_{per}$, i.e. the criterion for instability is fulfilled. Furthermore, from the observed magnetic probe signal $\beta_r = 8\pi n_r T/B^2 = 0.33$ with $n_r \approx 3 \times 10^{14}$ cm^{-3} follows a temperature of $T_{obs} \approx 31$ eV. From this value we calculate $\nu_e = 5.3 \times 10^7$. The mean ion mass in the considered plasma is $M_i = 20 \times 1.67 \times 10^{-23}$ g. Thus, the growth rate of the two-stream instability is of the order $\gamma \approx 3 \times 10^{10}$. Hence, the condition $\nu_e \ll \gamma$ is fulfilled too.

That a collisionless mechanism is contributing to the energy dissipation process in the wave front is also indicated by the discrepancy in the determination of T from the magnetic probe signal and from the effective conductivity which can be estimated from the measured width of the front. The distance for which B penetrates into the plasma is given by the magnetic Reynolds number $R_M = 4\pi V\sigma d/c^2 = 1$. Hence, σ can be determined from the measured V and d, $\sigma_{eff} = c^2/4\pi Vd = 1.8 \times 10^{13}$ esu. We can compare this value with Spitzer's formula which is based on the Coulomb collision frequency only, $\sigma = 2(2T)^{3/2}/\pi^{3/2} m^{\frac{1}{2}} Ze^2 c^2\ \ell n\ \Lambda$. Assuming $\ell n\ \Lambda \approx 10$ the measured conductivity σ_{eff} appears to correspond to an effective temperature of $T_{eff} \approx 1$ eV only. In conclusion, the observed conductivity is about 170 times smaller than the "collisional" one based on the temperature of $T \approx 31$ eV, $(\sigma_{eff}/\sigma_{cou}) = (T_{eff}/T_{obs})^{3/2} \approx 1/170$. This result indicates that the two-stream instability enhances the resistivity in the wave front by more than two orders of magnitude and thus the width of the front. The steep front disappears between $r = 1.5$ and 2 cm, where the thickness of the front is now of the same order as the radius, and the compressed magnetic field signal is reduced considerably. Obviously, the energy which was stored in the compressed B is suddenly released into the plasma and the plasma temperature increases. A fast diffusion of B back into the plasma is possible only when the conductivity of the plasma has been reduced. This is the typical effect associated with the occurence of instabilities. The increase of the thermal energy of the plasma is related to the emission of a second

light hump seen in Fig 2. In Fig. 2a the signal which indicates field compression is missing. Correspondingly the second light hump is also missing. In agreement with this interpretation Fig. 2b shows that compressed magnetic field signal starts to decrease at the time when the second light pulse begins to build up.

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Fig. 1. Total light photomultiplier and magnetic probe signals at r = 1.5 cm. B = 1500 Gauss.

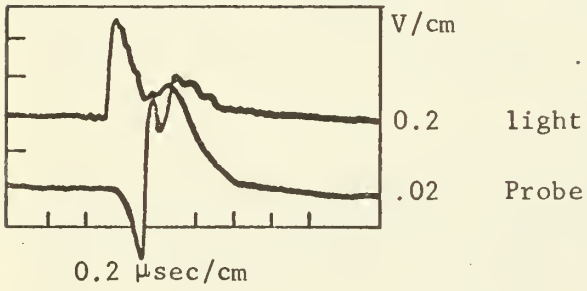
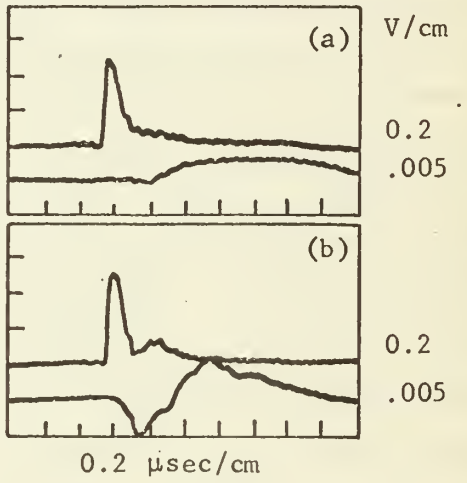


Fig. 2. Correlation between the structure of the wavefront and the light emitted from the plasma, probe at r = 3 cm.



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13. ABSTRACT

In Part A of the report the titles of the 12 sessions and the 5 invited lectures are summarized in the introduction. Concerning the content of the 117 presented papers, mainly the ones dealing with collisionless plasma phenomena are reviewed in the report, as for example: collisionless plasma heating by strong shock waves, turbulent heating, fluctuation spectrum during turbulent heating of a toroidal plasma, transformation and absorption of high frequency waves in a plasma, observation of anomalous resistivity, etc. Furthermore, an interesting effect concerning the anomalous scattering of laser light from a plasma is reported. The last chapter reviews a panel discussion on Tokamaks which started with a report on recent results given by L. A. Artsimovich and B. B. Kadomtsev.

Part B contains the paper No. 111, "Investigation of Instabilities and Collisionless Damping Mechanisms in the Front of a Laser Produced Plasma Interacting with a Magnetic Field" by F. Schwirzke, published in Proceedings Third European Conference on Controlled Fusion and Plasma Physics, Wolters-Noordhoff Publishing, Groningen, The Netherlands, 1969.

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